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SURFACE TEMPERATURE TRENDS AND VARIATIONS IN NEW ZEALAND AND THE SURROUNDING OCEAN, 1871–1993

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ABSTRACT

We compare homogenized series of maximum, minimum, and mean air temperature averaged over New Zealand, measured between 1871 and 1993, with rigorously quality controlled marine temperature data measured over the surrounding ocean surface. The marine data are those of sea-surface temperature (SST) and air temperature measured at night (NMAT) on board ship, both corrected for time-varying instrumental biases. There is mostly very good agreement between the variations in the three data sets on time-scales down to a season. Some disagreements are related to short periods of sparsely observed marine data, particularly during the World Wars. Differences also exist between trends in the maximum and minimum New Zealand temperatures (NZT), particularly in winter. In addition, interannual variations in winter NZT tend not to track those of nearby marine temperatures quite as well as happens in other seasons.

Although it is not the main purpose of the paper to discuss the causes of NZT change, New Zealand temperature is known to be influenced by the El Niño–Southern Oscillation (ENSO) phenomena. Tropical East Pacific SST variations are strongly related to ENSO and so are well correlated with NZT on time-scales of a few years to near a decade. We discuss these relationships, and also associations with Southern Hemisphere SST.

We conclude that annual NZT and NMAT over the nearby ocean surface have both warmed by about 0·7°C since the beginning of the century, with a slightly smaller increase in SST. This confirms previous work on the magnitude of the warming of New Zealand climate this century. Warming in NMAT and NZT in each season varies in a similar way, with consistently slightly smaller increases in SST. We also conclude that the UK Meteorological Office seasonal historical marine temperature data set appears to be generally of very good quality in the New Zealand region.

KEY WORDS: New Zealand; sea-surface temperature; night marine air temperature; correction techniques; El Niño; Southern Oscillation; surface temperature trends and variations; SST data sets; New Zealand temperature series.

INTRODUCTION

The extent to which existing temperature data are adequate to describe regional trends and variations over the land and the oceans is controversial. For the land surface this arises because artificial changes can be introduced into the data because of variations in the exposure of thermometers (Parker, 1994), alterations in observing methods and times (Karl *et al.*, 1986) and changes in the environment surrounding climate sites, such as those due to urbanization (Jones *et al.*, 1990; Karl *et al.*, 1993). Sea-surface temperature data (SSTs) have also suffered from artificial changes caused mainly by differences in the methods of observation. In the mid- to late nineteenth century wooden buckets were often used to collect sea-water and were largely replaced by uninsulated canvas buckets by the early twentieth century. A further change to the predominant use of engine intake thermometers occurred in the early part of the Second World War, followed after the war by the development of insulated sea-water buckets (Bottomley *et al.*, 1990; Folland and Parker, 1995). In recent decades, the increasing size of ships may have caused some artificial warming in engine intake sea-surface temperature measurements (Folland *et al.*, 1993; Kent *et al.*,

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1993). This possibility is not considered here because such time-varying biases are believed, on average, to have a small influence on SST. This is indicated by graphs of night marine air temperature (NMAT) versus SST in Bottomley *et al.* (1990) which show little evidence of a relative warming of open-ocean SST compared with NMAT in recent decades. A considerably bigger problem is that the ocean surface temperature data are often very incomplete because the density of ship observations varies greatly in space and time. This gives rise to sometimes large but mainly random uncertainties (Trenberth *et al.*, 1992).

Air temperatures measured on ships have been studied less than SST partly because of large and variable warm biases in the daytime data (e.g. Folland, 1971; Hayashi, 1974) and some differences in global trends compared with those of SST (Jones *et al.*, 1991). However Bottomley *et al.* (1990) showed that changes in marine air temperatures measured between sunset and sunrise, i.e. during the night (NMAT), agreed well with changes in bias-corrected SST once additional corrections were applied in NMAT. The corrections that are applied to the SST and NMAT data sets in the New Zealand region are independent of each other since the beginning of both data sets in 1854.

This study compares variations and trends in air temperature over New Zealand (NZT) with those of SST and NMAT in the vicinity of New Zealand. The long NZT series is especially valuable for this type of comparison because land and nearby ocean surface temperature variations are expected to be most similar for islands in the open ocean. The NZT data are also thought to be highly homogeneous from about 1870. Unusually, Stevenson screens have been used continuously since that time and much effort has gone into correcting NZT for changes of site and urbanization effects (Salinger *et al.*, 1993). In this paper we compare trends in annual and seasonal maximum, minimum, and mean NZT with those of nearby SST and NMAT on interannual, decadal, and multidecadal time-scales. We also provisionally assess the likely accuracy of the corrections that are applied to the marine temperature data in the New Zealand region.

NEW ZEALAND LAND TEMPERATURE RECORDS

Daily maximum and minimum temperature measurements in New Zealand were irregular until 1859, when the Colonial Secretary of the time, Mr Stafford, supplied standard instruments to observers at eight locations. Responsibility for the meteorological stations was transferred to Sir James Hector, Director of the Colonial Museum and Geology Department in 1867, and he introduced unusually uniform methods of observation (Hector, 1869). These included the introduction of Stevenson screens throughout the network, probably the earliest attempt to do this in any country. The thermometers were read at 0930 New Zealand Standard Time (NZST). Since then, instruments and observation methods have remained the same except for a change in the definition of NZST from true mean noon fixed at 172°E to true mean noon at 180°, and an observation time change to 0900 NZST. A change in the design of the Stevenson screen probably also occurred at an unknown time in the late nineteenth century from screens without a base to the modern type with a base (Parker, 1994), although there are no known records to prove this. This might have introduced some inhomogeneity into the diurnal range of air temperature but the amount is hard to assess. Improved reporting forms and meterological notebooks for entering the recordings at the time of observation were also introduced. Indeed, every effort was made to make the observations as good as the best of those in other parts of the globe.

Salinger *et al.* (1992) have made considerable efforts to homogenize maximum and minimum temperatures at 21 New Zealand climate stations, including those used here. The records were carefully refined by a number of methods. They were screened for inhomogeneities by examining station histories and comparisons were made between neighbouring stations to identify unrecorded site changes or other environmental changes near the climate station site. Procedures used to homogenize the data (Rhoades and Salinger, 1993) included cumulative sum plots and neighbouring station comparisons. For a few early records where neighbouring stations do not exist, other techniques were used to evaluate the significance of, and make adjustments for, suspected inhomogeneities (Rhoades and Salinger, 1993). This included the estimation of the size and standard error of a change point (discontinuity) in the temperature time series by (i) using annual data before and after the change points, (ii) using monthly data for specified symmetric intervals before and after the discontinuity, and (iii) estimating the most likely change points using the size of the change from an appropriate average. As a result, artificial trends have been minimized or removed to give equivalent 'single-site' series of maximum and minimum temperature.

THE NEW ZEALAND TEMPERATURE SERIES

Mean annual and monthly records from 77 climatological stations have been correlated over a 200 month period between 1951 and 1967 to establish the extent of spatial conformity in temperature trends and fluctuations across New Zealand (Salinger, 1981). Correlations of monthly temperature anomalies gave highly significant values of the correlation coefficient, r, between stations in all cases. The lowest correlation of 0·32 was between Havelock North in the east of the North Island and The Hermitage (Mount Cook) in the central South Island (see Figure 1). Only 66 of the 2926 possible pairs gave $r < 0{\cdot}50$. Thus temperature anomalies throughout New Zealand are often quite similar in a given month. On the annual time-scale, correlations were much higher so that the lowest value of r between time series from the seven sites with long records in Figure 1 was 0·73. Accordingly, the homogenized records from the seven long-period sites in Figure 1 which cover well the land area of New Zealand were chosen to form the NZT series (e.g. Salinger, 1979, 1980, 1981). Anomalies from the 1951–1980 normal period were calculated for each site and combined and averaged to form the NZT anomaly series. The high coherence of the

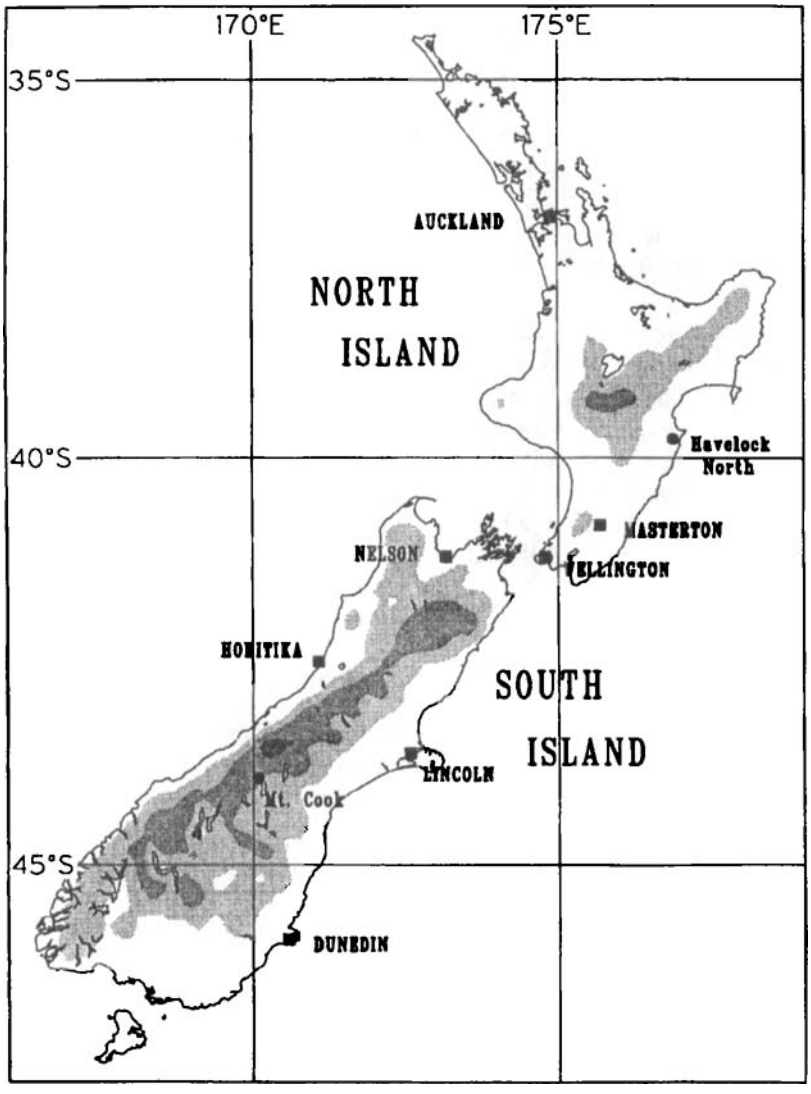


Figure 1. Location of the seven climate sites used in the New Zealand temperature (NZT) series, and the Havelock North and Mt Cook sites. Stippling represents land areas above 1000, 2000 and 3000 m

Table I. Stations used in the New Zealand temperature series

Station	Period of record
Auckland	1855–
Dunedin	1853–
Hokitika	1863–1880, 1894–
Lincoln	1864–
Masterton	1908–
Nelson	1863–1880, 1906–
Wellington	1863–

stations can be judged by noting that their average intercorrelation over 1951–1980 was 0·81 (annual), 0·77 (winter), 0·72 (spring), 0·81 (summer), and 0·81 (autumn).

Equal weighting of the chosen stations was preferred because the correlations between the seven stations do not fall off in the same way with distance everywhere. Thus Masterton is on the opposite side of mountains from Wellington, reducing their intercorrelation, and Nelson is likewise less well correlated with Hokitika or Wellington than its distance from either would indicate. To underline the fact that the NZT series created in this way represents the land area of the whole country very well, the correlation between annual mean NZT and an areally weighted series for New Zealand for the period 1956–1980 based on 46 stations was calculated to be 0·98 (W. J. Maunder, pers. comm.).

From 1871 to 1880, data come from only six of the seven sites and from 1881 to 1893, just four sites, but fortunately these still well cover the extent of New Zealand (Table I). From 1908 the data series is complete for all seven sites.

Changes in the station environment afflict all temperature data but again these have been small for many of the sites used here. Of the seven sites, four (Masterton, Hokitika, Nelson (Appleby), Lincoln) are at rural locations (Salinger *et al.*, 1992). The Wellington site is in the Botanical Gardens at the top of a hill in a very windy location, and the Auckland site is at the sewerage treatment plant on the edge of a harbour, which is still not affected by Auckland urbanization. The present Dunedin site at Musselburgh is in the middle of a park with surrounding bungalow housing between extensive water masses; broadly similar housing has been present ever since records commenced. So temperatures at the more urban sites are unlikely to be affected significantly by growth or industrialization. All New Zeland air temperature data series have been used in the form of departures (anomalies) from averages for 1951–1980.

MARINE TEMPERATURE SERIES

The SST and NMAT data have been taken from an updated version of the Global Ocean Surface Temperature Atlas (GOSTA) marine data set (Bottomley *et al.*, 1990). The corrections to SST in the GOSTA data set are more recent, being those published in Folland and Parker (1995). However, these do not differ greatly from those in the GOSTA Atlas. Some enhancements to the SST data have also been made, particularly the inclusion of data from the USA Comprehensive Ocean–Atmosphere Data Set (COADS) (Woodruffe *et al.*, 1987) for regions where GOSTA had no data. This affects mainly the eastern half of the Pacific. The NMAT data have not been enhanced using COADS data because COADS does not distinguish daytime from night-time air temperatures; however, additional NMAT observations are included from other sources. The versions of the GOSTA data sets used here are the Meteorological Office Historical Sea Surface Temperature Data Set version 5 (MOHSST5) and the Meteorological Office Historical Night Marine Air Temperature Data Set version 3 (MOHMAT3).

A few of the analyses use a new SST data set, the Global Sea Ice and Sea Surface Temperature Data Set (GISST, Parker *et al.*, 1995). The GISST is nominally globally complete and was designed originally for forcing global climate models. Interpolation and extrapolation is done in ways not included in MOHSST. Chief among these is the blending of available data and the 1951–1980 GOSTA climatology over data voids using the Poisson equation

technique of Reynolds (1988). We have used GISST when comparing NZT with tropical East Pacific SST because it is likely to give a better analysis of the interannual variations that are important in that comparison. However, GISST is less suitable for climate change studies because the interpolation technique relaxes data voids towards the background GOSTA climatology. This will tend to create long-term variations in SST anomalies that will be biased a little too small. The basic resolution of all the marine data sets is monthly 5° latitude × 5° longitude, although the background GOSTA climatologies have a 1° × 1° calendar 5-day resolution that is used in quality control.

The most important marine area used here is the region immediately surrounding New Zealand, bounded by 30°–50°S, 165°–180°E. This contains 12 ocean areas 5° × 5°, eight of which are partly occupied by the New Zealand land mass. In addition, comparisons are made with tropical East Pacific SST defined by an area 160°–80°W, 10°N–10°S, and with the whole Southern Hemisphere Ocean. As explained above, GISST has been used for the tropical East Pacific but MOHSST5 has been used for the remaining analyses. Note that the Southern Hemisphere SST series can be based on widely scattered and incomplete data. Monthly mean marine series are calculated from an area-weighted average of the available 5° × 5° areas. A monthly 5° × 5° value is considered usable if it contains at least one quality controlled data value. (Bottomley *et al.* (1990) give details of the complex processing that creates the 5° × 5° monthly values.) Seasonal series are created by averaging the 5° × 5° monthly anomalies into seasonal means (a minimum of 1 month is needed for a single season) and then by averaging the seasonal 5° × 5° values over the region. Annual values are the averages of available seasonal values. Thus the marine series can be based on widely varying numbers of 5° × 5° values when data are incomplete.

COMPARISON OF NEW ZEALAND AND SURROUNDING MARINE TEMPERATURES

The main comparisons have been made with SST and NMAT data in the area surrounding New Zealand described above. Comparisons have been done: (i) using unfiltered annual and seasonal data; (ii) using data that has been low-pass filtered on time-scales approximately longer than a decade; and (iii) using data that has been low-pass filtered on time-scales longer than about 40 years. The filtering has been carried out using a recursive estimation technique based on the Kalman filter, which is especially suitable for non-stationary series (Young *et al.*, 1991; Chatfield, 1992; Lane, 1992). This technique places a smooth line through the time series whose slope is assumed to vary as an integrated random walk process. The local smooth curve is estimated twice by carrying out a forward and then a backward sweep and the average taken. To create nearly unbiased filtered values at the beginning and end of each series, 15 dummy data values are added to the beginning and end of each series. These are set to equal the average of the first or last 10 observed values and removed after filtering has been completed.

The reliability of the marine data for the area surrounding New Zealand depends considerably on the completeness of the coverage of the 12 contributing 5° × 5° areas. Figure 2(a) shows the annual numbers of original observations of SST and NMAT between 1871 and 1993, and Figure 2(b) shows the percentage of seasonal 5° × 5° areas sampled in each year after completion of the analysis procedure (the maximum number of areas × seasons sampled in a year is 48). The number of NMAT observations in Figure 2(a) are generally about 60 per cent of the number of SST observations. However, the percentage coverage in Figure 2(b) is generally more than 60 per cent of the corresponding SST coverage and reaches 100 per cent in many recent years. This arises because there will often be many observations included within a single 5° × 5° area and, despite their fewer number, the NMAT data are almost as well distributed spatially as are the SST data. The severe reductions in the SST percentage coverage centred on 1918 (29 per cent), 1941 (35 per cent) and 1944 (46 per cent) correspond to the two World Wars. Thus SST coverage for 1918, 1941, and 1944 is less than in any late nineteenth century year. For NMAT, 1941 (21 per cent) has least coverage followed by 1872. The SST coverage over much of the late nineteenth century is surprisingly good.

The main purpose of the paper is to compare variations and trends in New Zealand and surrounding marine temperatures. So tests were carried out to determine if these vary in phase. For 1871–1993, the best correlation between annual mean NZT and annual SST occurred when SST lagged NZT by 1 month, but the best correlation of NZT with NMAT was simultaneous. This can be understood if SST in the extratropical New Zealand region is forced mainly by anomalies of overlying air temperature, which are in turn forced mainly by changes in regional weather patterns, although an influence of changes within the ocean is also likely. Bjerknes (1964) and later authors have pointed out that the former is an important factor on seasonal time-scales for the extratropical North Atlantic.

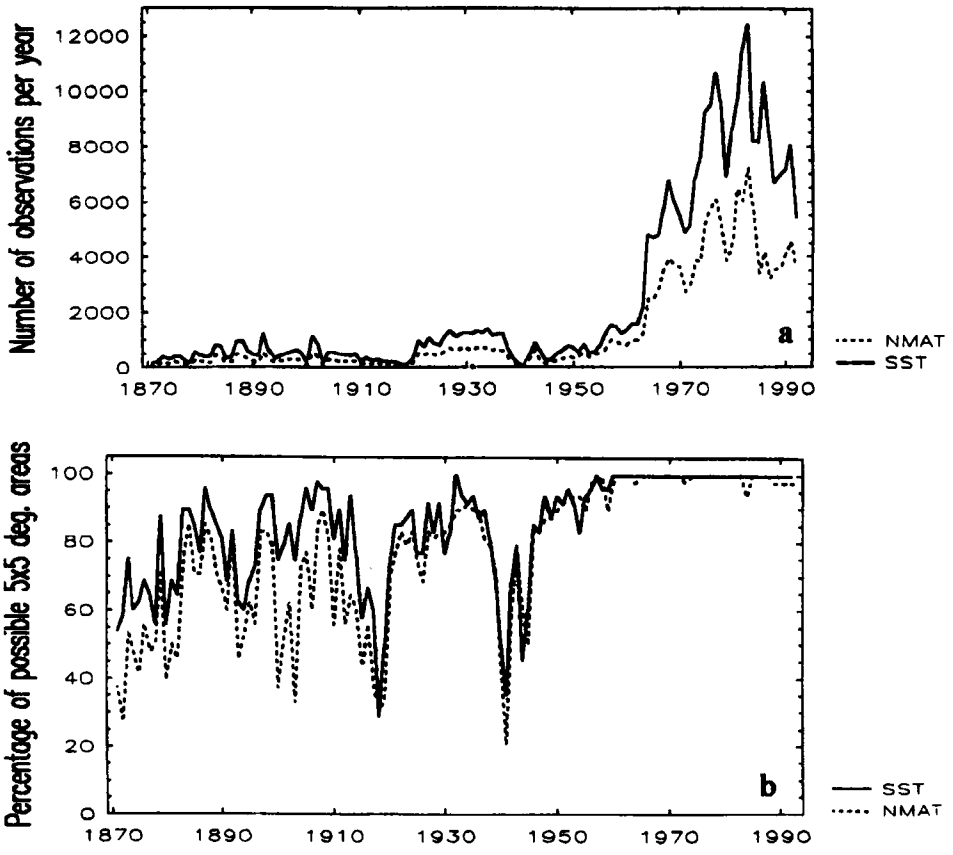


Figure 2. (a) Annual numbers of sea-surface temperature and night marine air temperature observations for 165°–180°E, 30°–50°S, 1871–1993. (b) Annual percentages of the maximum possible number of seasonal 5° × 5° areas that are available for sea-surface and night marine air temperature

In addition, a close correspondence between NMAT and SST anomalies occurs on time-scales from a season to a century over all open ocean areas of the globe, as illustrated in the time series given by Bottomley *et al.* (1990). (We do not expect to see a close relationship between NZT and SST on monthly time-scales, e.g. Basher and Thompson, 1996, so monthly time-scales are not analysed.) Accordingly, in most of this paper, annual NZT and NMAT are measured from December to November and annual SST is measured from the following January to December. Summer values are based on December to February for NZT and NMAT and January to March for SST, and similarly for other seasons. However, annual NZT is defined to be for January–December in remote comparisons with Tropical East Pacific and Southern Hemisphere SST where a lag does not seem appropriate.

The next two sections examine unfiltered relationships between NZT, SST, and NMAT in order to compare their similarity on annual and seasonal time-scales.

UNFILTERED ANNUAL RELATIONSHIPS

Here we study the interannual correlations of NZT with surrounding marine data, including those with uncorrected SST and NMAT data. The latter helps to gain an initial impression of whether the corrections improve the agreement with NZT. As discussed in Bottomley *et al.* (1990), corrections to NMAT (their list D, p. 10) in most parts of the world, including New Zealand, vary from −0·15°C, up to 1890 at all times of the year, decreasing linearly to zero in 1930, and reflect the systematically changing heights of ships' decks. There is also a short period in World War II (1942–1945) with considerably larger corrections to NMAT. Corrections to SST up to 1941 are

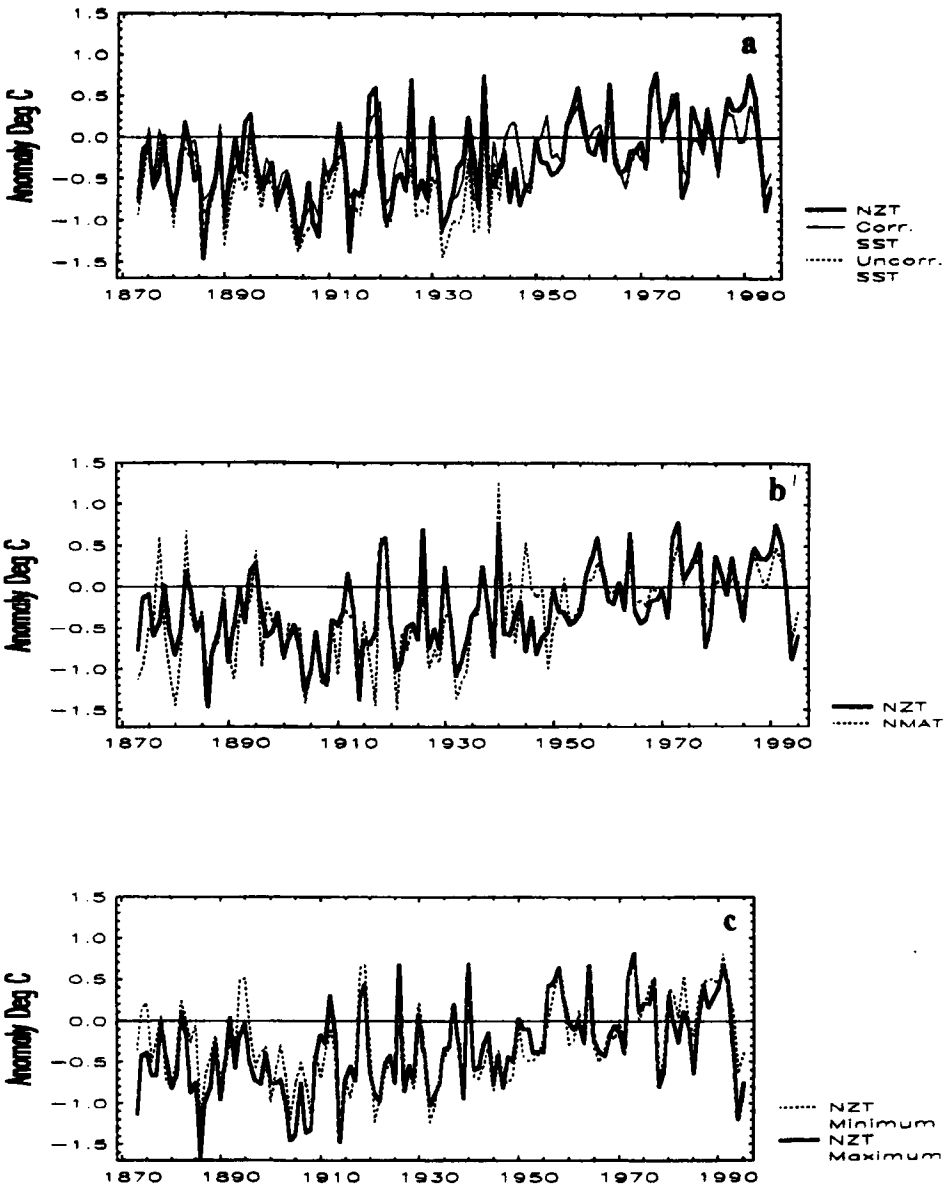


Figure 3. (a) Annual mean NZT anomalies (thick line), annual corrected SST anomalies (thin solid line) and uncorrected SST anomalies (before 1942) (dashed line) from MOHSST5. Anomalies from 1951–1980. (b) Annual mean NZT anomalies (thick line), and corrected NMAT anomalies (dashed line) from MOHMAT3. (c) Annual maximum (solid line) and minimum (dashed line) NZT anomalies

much more complicated but in the New Zealand region are always of opposite sign to those for NMAT and slowly increase up to 1941 before suddenly becoming zero in December 1941 (Folland and Parker (1990, 1995) give details).

Figure 3(a) shows unfiltered annual mean NZT and corrected and uncorrected SST for the surrounding ocean area from 1871 to 1993. Figure 3(b) shows a similar graph for annual mean NZT and corrected NMAT, and Figure 3(c) compares annual maximum and minimum NZT. There is clearly a generally good correlation between annual NZT, NMAT, and SST, with uncorrected SST before 1942 tending to be cooler than NZT (Figure 3(a)). Annual maximum and minimum NZT show mostly quite similar anomalies (Figure 3(c)), although there is a tendency for those of minimum temperature to be relatively higher before about 1900. All series show a relatively cool period in the nineteenth century, with a minimum soon after 1900 followed by a general rise until about 1975. The strong

Table II. Standard correlation between unfiltered annual mean, maximum, and minimum New Zealand air temperature (NZT) and marine data sets

Period	NZT	Uncorrected SST	Corrected SST	Uncorrected NMAT	Corrected NMAT
1871–1941	Maximum	0·68	0·73	0·67	0·69
	Minimum	0·76	0·76	0·75	0·75
	Mean	0·74	0·77	0·74	0·75
1949–1993	Maximum		0·88		0·90
	Minimum		0·77		0·87
	Mean		0·85		0·93
1871–1993	Maximum		0·81		0·75
	Minimum		0·79		0·76
	Mean		0·82		0·77

interannual variability is shown by the low first serial correlations of detrended annual mean NZT and corrected SST data for 1871–1993, which are 0·21 and 0·20 respectively. Detrending was carried out using the 40-year filter discussed later and therefore includes the fact that the trends are non-linear. This low persistence of annual values is partly related to ENSO.

Standard correlations between NZT and corrected and uncorrected (where appropriate) SST and NMAT are shown in Table II for 1871–1993, 1871–1941, and the best observed period 1949–1993.

The period 1871–1941 is analysed separately to compare the correlations between NZT and corrected and uncorrected SST. It also allows a comparison of such correlations with corrected and uncorrected NMAT, bearing in mind that no corrections to NMAT are applied after 1930. All correlations are in the range 0·67 to 0·93. It is difficult to assess their significance because the trends are large compared with the interannual variability, and the usual methods of assessing the numbers of degrees of freedom (e.g. Quenouille, 1952) that assume stationarity give inconsistent results. However, it is clear that the corrected marine data 'explain' over 50 per cent of the variance of annual mean NZT overall and, after 1949, around 80 per cent. Uncorrected SST values have a slightly lower correlation over 1871–1941 than the corrected values. Standard correlation is not sensitive to a mean correction but is sensitive to a time-varying one. This suggests that the time-varying component of the SST corrections of Folland and Parker (1995) has some skill in the New Zealand region if we accept the homogeneity of the NZT record. Uncorrected NMAT over 1871–1941 also has slightly lower correlations overall with NZT than corrected NMAT, indicating that there might also be a little skill in the time-varying component of these rather small corrections. In World War II, Figures 3(a) and 3(b) show almost no correlation between annual NZT and NMAT and little with SST. This can be attributed to the very sparse marine data (Figure 3(a)). (We have not tested the considerably larger NMAT corrections in World War II because of this sparse data.)

For the much better observed period 1949–1993, by contrast, NMAT has a higher correlation with mean NZT (0·93) than does SST (0·85). This suggests that if well enough observed, air temperatures over the surrounding ocean are (not surprisingly) better correlated with air temperatures over New Zealand than are SST values.

The ocean region around New Zealand is inevitably rather larger than the land area of New Zealand itself. So the standard deviations of the marine and NZT series may differ even if they are genuinely very well related. The standard deviations may also change through time, partly because of poorer marine data in earlier years, which tends to increase standard deviation, and partly because of real changes including the influence of trends. The standard deviations of all data sets tend to be greatest in earlier years, notably for the marine data. In 1871–1941, annual NMAT has the highest standard deviation (0·54°C) compared with SST (0·39°C) and mean NZT (0·46°C), whereas in 1949–1993 the standard deviation of annual NMAT is the lowest at 0·26°C, compared with SST (0·33°C) and mean NZT (0·42°C). The reason for the lower standard deviation of NMAT than SST in 1949–1993 is not completely clear but partly reflects the good NMAT data in the latter period. The fact that the standard deviation of NMAT is less than that of NZT in 1949–1993 is reasonable given that the marine area is considerably larger. Thus if additional historic data became available, the biggest impact may be on NMAT before 1949, when the standard deviations of annual NMAT could fall substantially. Nevertheless, the agreement between NMAT and NZT in Figure 3 is very encouraging overall.

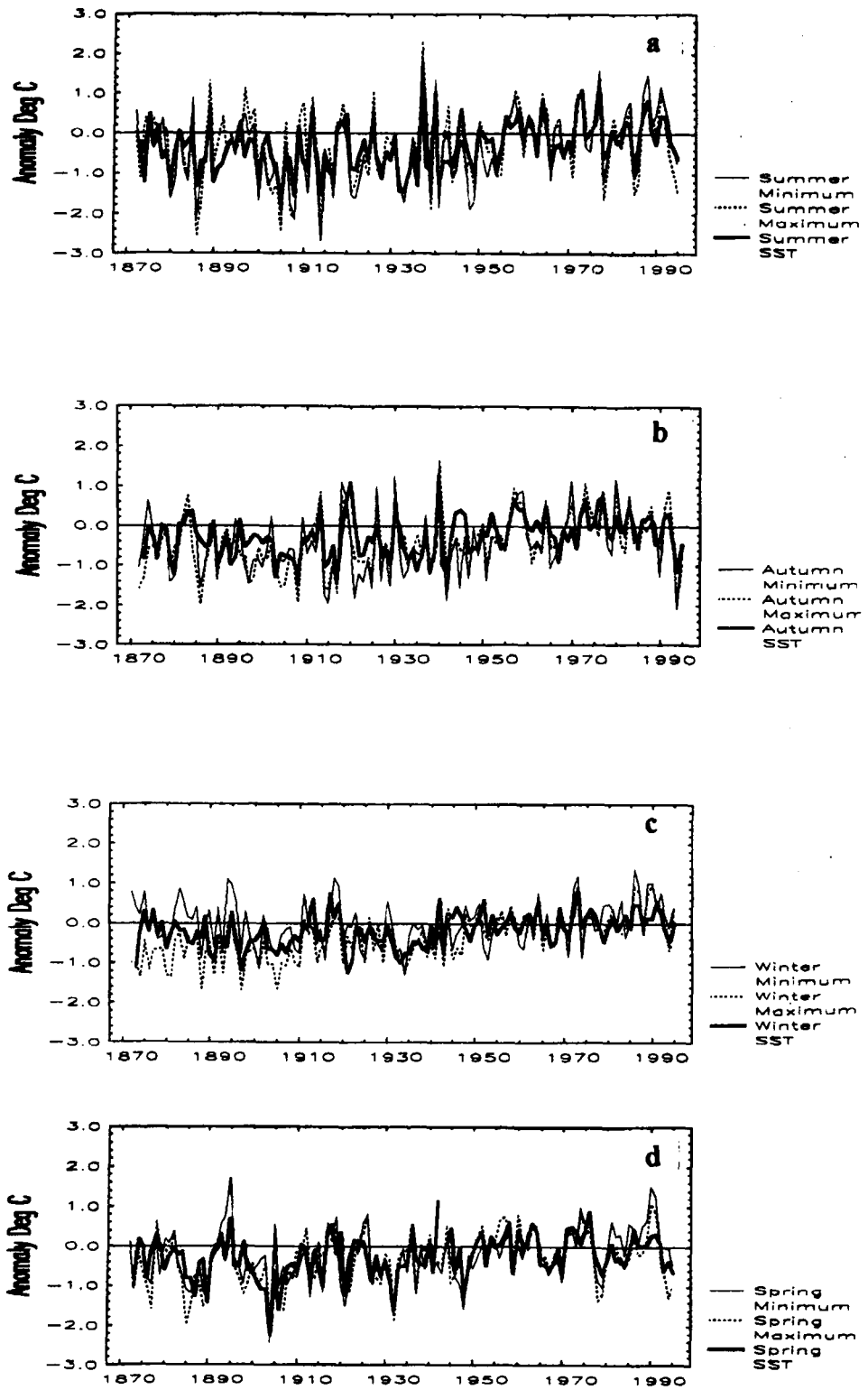
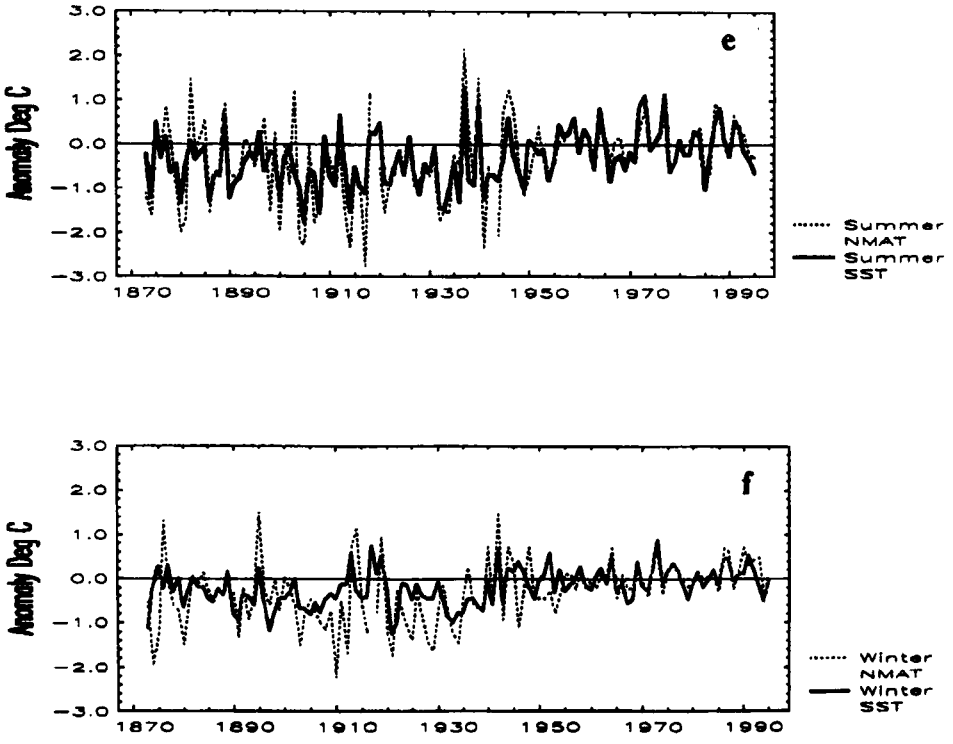


Figure 4. (a) Maximum (dashed line) and minimum (thin line) summer NZT anomalies, and summer corrected SST anomalies (thick line) for 165°–180°E, 30°–50°S, 1871–1993. (b) As (a) but for autumn. (c) As (a) but for winter. (d) As (a) but for spring. (e) Corrected SST (thick line) and NMAT (dashed line) values for summer for 165°–180°E, 30°–50°S, 1871–1993. (f) As for (e) but for winter.



Figures 4(d)–4(f)

UNFILTERED SEASONAL RELATIONSHIPS

Seasonal NZT values are likely to be less well correlated with surrounding SST and NMAT because transient synoptic features will have more influence on NZT without much affecting SST, and may affect NMAT over the larger marine area differently. Another factor is data coverage, which tends to be less complete than for the annual time-scale. Before about 1920 there was a marked seasonal variation in the seasonal NMAT data coverage as measured by the total number of 5° × 5° areas with an analysable constituent monthly NMAT anomaly after quality control. The minimum coverage was in winter, with a considerable number of winters having less than a 40 per cent coverage. The poor NMAT coverage in all seasons before 1920 leads to an artificially high standard deviation of seasonal, and especially winter, NMAT.

Figure 4(a–d) shows seasonal maximum and minimum NZT values plotted for each season against corrected seasonal SST, and Figure 4(e and f) shows NMAT versus SST for winter and summer, all for 1871–1993. There are insufficient data to create a seasonal value for the following seasons; SST: spring 1941; NMAT: summers 1917 and 1941, winter 1916.

Before discussing the seasonal correlations we comment on the likely effects of variations in data coverage. A useful method is to note the standard deviation of SST or NMAT as a fraction of that of NZT (f_{sst} and f_{nmat}). Thus in 1949–1993, f_{nmat} varied from 0·54 in summer to 0·71 in winter; SST based on MOHSST5 shows a similar narrow range of seasonal f_{sst} from 0·65 in autumn and winter to 0·82 in spring. The seasonal variations in f are clearly almost random in 1949–1993 and reflect the fact that the marine temperatures around New Zealand were mostly well sampled in this period. However, in 1871–1941, f_{nmat} varies from 1·12 in summer to 1·64 in winter, whereas f_{sst} for corrected SST varies between 0·70 in summer and 0·92 in spring (0·88 in winter), only a little greater than that for 1949–1993. The differences in f_{sst} and f_{nmat} in 1871–1941 are at first sight larger than might be expected

from the differences in data coverage. However, the high values of f_{nmat} can be explained by lower temporal persistence in individual NMAT observations compared with SST observations combined with a higher standard deviation of individual NMAT observations. So NMAT is more *sensitive* to poor coverage than SST. Thus unfiltered seasonal NMAT variations are, as expected, considerably larger than, and less well correlated with, SST before 1950 (Figure 4(e and f)).

Figure 5(a) shows seasonal correlations between mean NZT, SST, and NMAT for 1949–1993. Maximum and minimum NZT (not shown) give similar but slightly lower correlations. The SST correlations are very high in summer ($r = 0{\cdot}90$), with the lower correlations in other seasons and a distinct minimum in winter ($r = 0{\cdot}62$). Maximum and minimum NZT give correlations of 0·89 and 0·85 with SST in summer and 0·71 and 0·51 in winter. Because the interseasonal coverage of marine data does not vary much in 1949–1993, much of the seasonal change in correlation may be genuine. The NMAT does not show such a distinct seasonal change. Quite high correlations with mean NZT occur in all seasons, varying from $r = 0{\cdot}92$ in autumn to $r = 0{\cdot}78$ in spring.

Figure 5(b) shows the correlations in the less-well-observed period 1871–1941. In Figure 5(b), a fairly similar annual cycle is seen in correlations between SST and NZT as occurs in 1949–1993 but with values reduced by 0·1–0·15. Thus the variance of NZT explained by SST is about 20 per cent less in each season than 1949–1993. The NMAT shows a distinct seasonal cycle of correlation in 1871–1941, unlike 1949–1993, which is likely to be related to the seasonal cycle in NMAT data coverage at that time, with a minimum correlation in winter. Figure 5(b) also compares seasonal correlations between mean NZT and uncorrected and corrected SST from MOHSST5 for 1871–1941. The corrected values give mostly slightly greater correlations, as was observed for the annual data. As discussed for annual data, the generally slightly higher correlations for corrected SST imply that the time-varying component of the SST corrections may have skill in all seasons except perhaps spring.

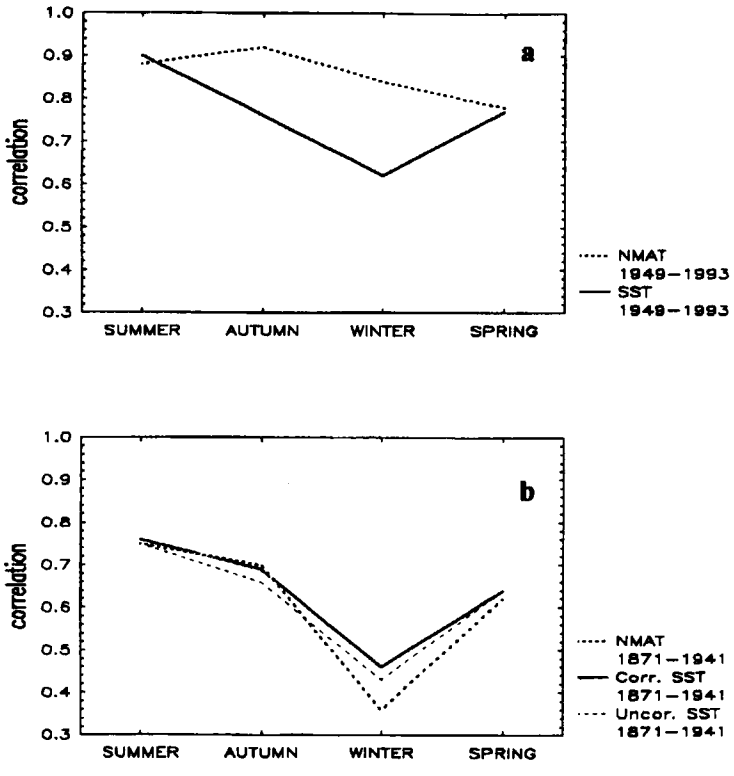


Figure 5. (a) Correlation between seasonal New Zealand air temperature (NZT), corrected NMAT (dashed line) and corrected SST (solid line) in 1949–1993. (b) Correlation between seasonal NZT and NMAT (thick dashed line), corrected SST (solid line), and uncorrected SST (thin dashed line), 1871–1941

In winter, maximum and minimum NZT anomalies varied considerably differently before about 1910 (Figure 4(c)) with minima being relatively warmer than maxima. However, the SST data tend to vary almost as their average, perhaps indicating a real change in the diurnal range of NZT or compensating changes in time-varying biases in maximum and minimum NZT. Other seasons show much more similar changes in maximum and minimum NZT before 1910.

PRELIMINARY TESTS OF MEAN CORRECTIONS TO MARINE DATA IN THE NEW ZEALAND REGION

Here we test in a preliminary way whether the mean levels of the corrected SST and NMAT anomalies are more similar to those of NZT than their uncorrected values in an attempt to determine if the corrections have value. The extent to which the NZT should agree with the marine data is not completely clear, as we cannot be certain of the homogeneity of the NZT values nor of whether the relationships between NZT anomalies and marine anomalies may have differed through time. Nevertheless we consider that the following analyses provide useful evidence about the validity of the marine corrections.

The SST corrections are largest in late autumn and early winter (Folland and Parker, 1995). Their annual average magnitude for 1871–1941 is 0·23°C in the region studied here. Making the assumption that the mean anomalies of NZT, NMAT, and SST should be the same in each season when averaged over about half a century, Figure 6(a) compares uncorrected and corrected NMAT and mean NZT in each season averaged for 1871–1914. 1914 was chosen as the last year for comparison because the correction to NMAT falls to −0·06°C in 1914 and NMAT data deteriorates in 1915. Figure 6(b) similarly compares corrected and uncorrected SST with mean NZT for 1871–1941. Uncorrected SST is significantly colder than NZT at the 95 per cent confidence level in all seasons and in the

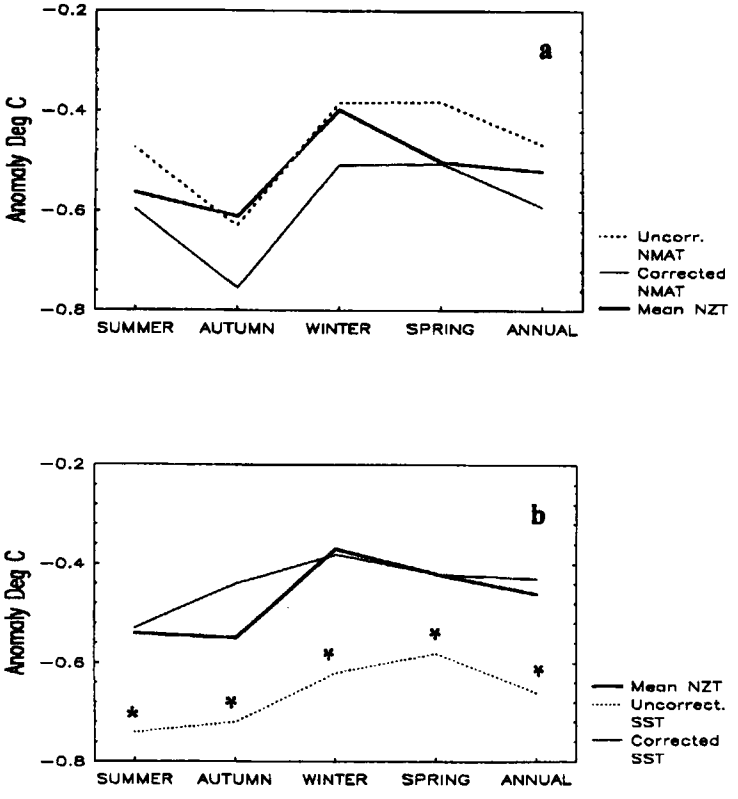


Figure 6. (a) Comparison of corrected (thin line) and uncorrected (dashed line) NMAT anomalies with those of annual mean NZT (thick line) over 1871–1914 in all seasons and the annual mean. (b) As (a) but SST in 1871–1941; significant differences from NZT are starred

annual mean according to one tailed *t*-tests, whereas corrected SST has very low and insignificant *t* values. Uncorrected NMAT is not different significantly from mean NZT over 1871–1914 in any season but neither is corrected NMAT, despite a mean reduction of corrected NMAT by 0·12°C. This arises because uncorrected NMAT is slightly warmer than NZT and corrected NMAT is slightly colder.

So we conclude tentatively that correcting SST by an average of +0·23° over 1871–1941 is a worthwhile improvement. Corrected NMAT is in reasonable agreement with mean NZT in all seasons. Given this encouraging result, we now selectively compare NZT with marine data filtered to remove less than (i) decadal and (ii) about 40 year time-scales.

DECADALLY FILTERED TIME SERIES

Figure 7(a) compares decadally filtered annual NZT with decadally filtered corrected annual SST and NMAT for 1871–1993, and Figure 7(b) compares filtered annual maximum and minimum NZT with filtered annual SST. This low-pass filter, as explained above, passes a period of 10 years, with half amplitude. Figures 7(c)–(f) are similar to Figure 7(a) but show filtered seasonal values. Any missing seasonal data are linearly interpolated.

Firstly, Figure 7 highlights the poor agreement between NMAT or SST, and NZT, in World War II. However, despite this bad period, the correlations between NMAT and annual maximum, minimum, and mean NZT over 1871–1993 are 0·87, 0·83, and 0·88 respectively. For SST, the correlations are 0·89, 0·82, and 0·87. These correlations are considerably better than for unfiltered annual NMAT and somewhat better than for unfiltered annual SST (Table II). Seasonal correlations are also better than for unfiltered data but the differences are, not surprisingly, small for SST in summer where the correlation is very high for unfiltered data. Thus filtered mean summer NZT has a correlation of 0·84 with SST (0·82 for unfiltered data). For NMAT the correlation is distinctly higher than for unfiltered data (0·81 compared with 0·74). The biggest differences occur in winter, when correlations are lowest. Thus filtered winter SST has a correlation of 0·77 with mean NZT (0·58 unfiltered) and filtered NMAT has a correlation that reaches 0·71 (unfiltered 0·53), despite the fairly poor agreement in much of the period 1900–1950 (Figure 7(e)). Note that World War II is especially poor for NMAT in spring.

Prominent in Figure 7 are fluctuations with a period centred around 14–18 years in all seasons except winter. This fluctuation is discussed in the section below that compares NZT with Tropical East Pacific and Southern Hemisphere SST.

It is worth noting that the lower winter correlations can be explained partially by the regional atmospheric circulation (Maunder, 1971). In winter, the incidence of blocking is highest, with blocking anticyclones most frequent over southern New Zealand and with related cyclonic activity in the North Tasman Sea and over northern New Zealand. The result is often to decouple winter NZT anomalies during the frequent stable anticyclonic episodes from the anomalies of the surrounding atmosphere and thus the NMAT and SST.

40 YEAR 'TREND' FILTERED SERIES

This 'trend' time-scale has been chosen to highlight changes that are less likely to be dominated by internal climate variability (such as ENSO) compared with changes in climatic forcing due to enhanced greenhouse gases, human-induced tropospheric aerosols and slowly varying natural forcing factors, such as solar output changes and variations in oceanic circulation. Figure 8(a) shows trend-filtered annual mean NZT, SST, and NMAT for 1871–1993. Figure 8(b) shows trends for maximum and minimum NZT and SST, Figures 8(c)–(f) are like Figure 8(a) but refer to the individual seasons.

In Figure 8(a) (annual mean data), the lowest temperatures occur at the beginning of the twentieth century and not at the beginning of the record (Figure 3 confirms that this is not an artefact of the smoothing). The coolest filtered values are in 1901–1902 for SST, 1906 for NMAT and 1903–1904 for mean NZT; the corresponding highest values are for 1973, 1979 and 1985 and 1986–1987. The pronounced warming evident in Figure 8(a) therefore stops in the marine data at times centred on the 1970s.whereas warming of NZT stops only in the early 1980s, with hardly any change since. The magnitude of warming in all three series since the 1990s is fairly similar, although least in SST: 0·73°C in mean NZT, 0·72°C in NMAT and 0·60°C in SST. The NMAT is cooler than for the other two variables between 1910 and 1930 by about 0·1°C but the minimum value occurs at about the same

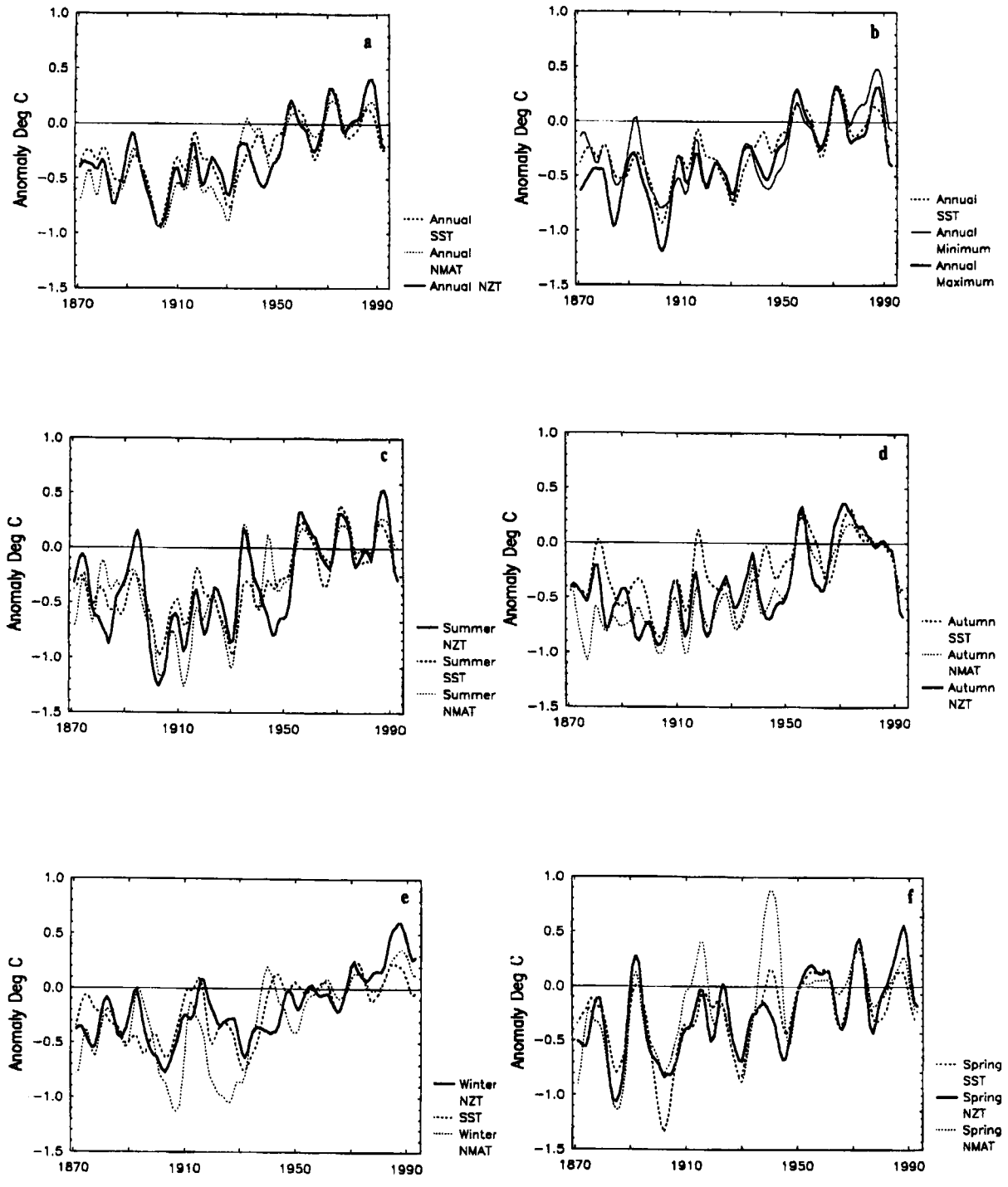


Figure 7. (a) Decadally filtered annual NZT anomalies (solid line), corrected NMAT anomalies (thin dashed line) and corrected SST anomalies (thick dashed line), 1871–1993. (b) As (a) but annual maximum (solid line) and annual minimum NZT anomalies (thin solid line) and SST (dashed line). (c) As (b) but summer. (d) As (b) but autumn. (e) As (b) but winter. (f) As (b) but spring

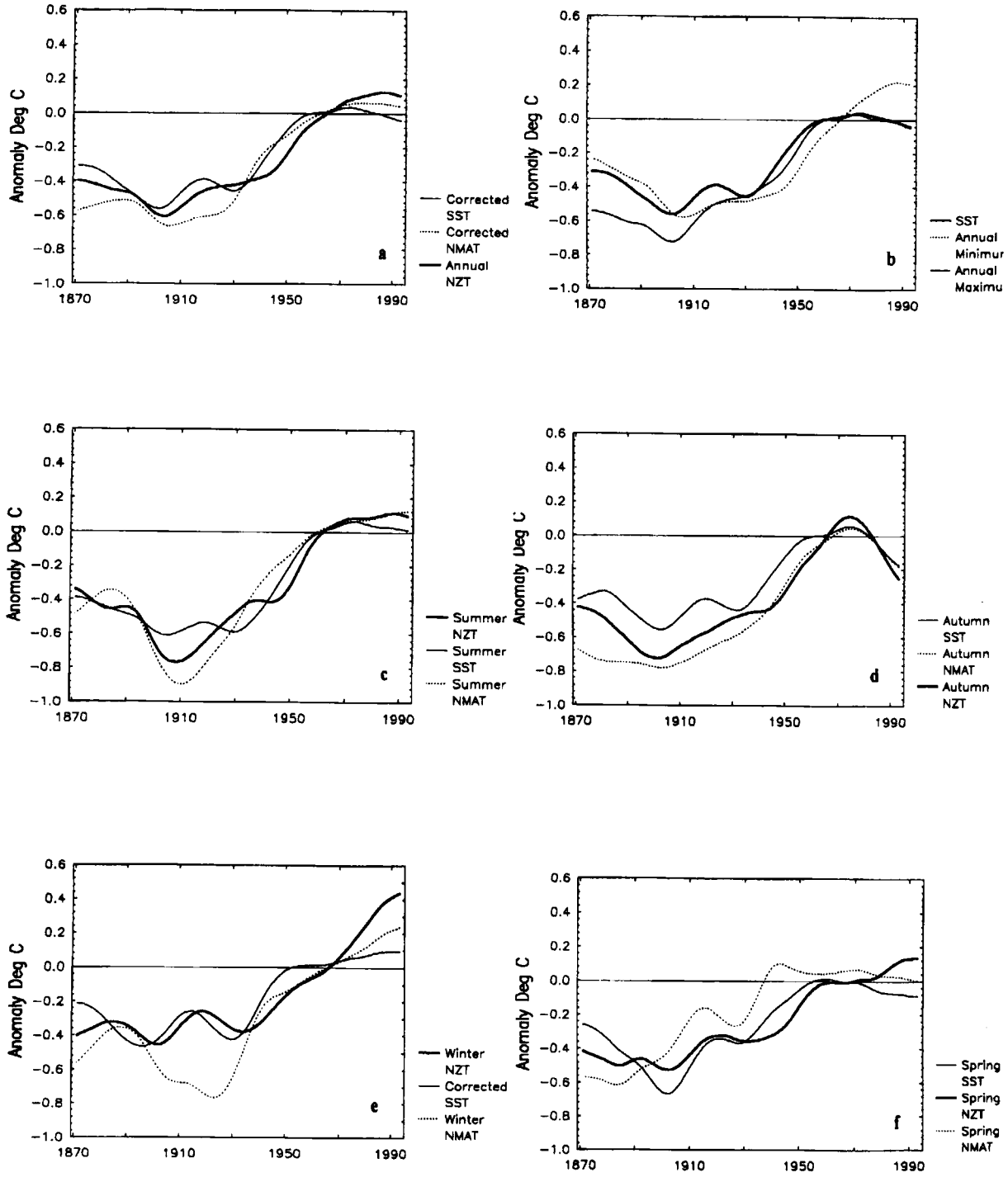


Figure 8. (a) Trends of annual mean NZT anomalies (thick solid line), annual corrected SST anomalies (thin solid line), and corrected NMAT anomalies (dashed line) for 165°–180°E, 30°–50°S for 1871–1993. (b) As (a) but annual maximum (thin line) and minimum (dashed line) NZT anomalies and similarly defined SST. (c) As (b) but summer. (d) As (b) but autumn. (e) As (b) but winter. (f) As (b) but spring

time. Maximum and minimum NZT (Figure 8(b)) show a similar overall warming to that of mean NZT, but warming of the maximum appears to have ceased around 1970 whereas warming of the minimum continued to the late 1980s. Again the coolest value is observed in the 1900s in both series, with a marked slowing of warming in maximum and minimum NZT (and therefore mean NZT) centred near 1930. There was an actual cooling of annual SST between about 1920 and 1930.

Figure 8(c), for summer, gives quite similar trends for mean NZT, SST, and NMAT. Here warming has been slightly greater than that for the annual mean. Again the lowest values are all in the first decade of the twentieth century. This is also true for mean maximum and minimum NZT (not shown). The three series illustrated show a recent marked slowing of warming, with a peak in mean NZT in the late 1980s, no warming of SST since the 1970s but a slight continuing warming of NMAT. The change in mean summer NZT of 0·88°C since the 1900s is slightly less than that in NMAT (1·02°C) and greater than that in SST (0·67°C). The timing of the changes in maximum and minimum summer NZT differs a little from mean NZT, with a warming of 0·74°C in maximum NZT and the largest warming in any of the series, 1·23°C, in minimum summer NZT.

Figure 8(d), for autumn, again gives quite similar estimates of warming for all time series, comparable to those of summer. The coldest period for autumn in all data sets is centred on the early 1900s and all series indicate a cessation of warming centred on the middle 1970s followed by a distinct cooling of about 0·3°C. The warming of mean autumn NZT between the 1900s and mid-1970s, 0·87°C, is similar to that of NMAT, 0·85°C, and somewhat greater than that for SST, 0·63°C. Mean maximum and minimum autumn NZT warmed by 0·96°C and 0·83°C respectively over the same period. Autumn is the only season that clearly shows a recent cooling.

Figure 8(e), for winter, gives the most diverse results and differs most from autumn in that winter warming still continued in 1993. The poorer agreement between the winter data sets than those in other seasons is probably partly due to sparse NMAT data in much of the first part of the century. The changes in temperature also have been more complex. A second minimum centred on the early 1930s (visible in Figure 8(a) as well) is clearly seen in mean NZT and in SST. The probably too cool NMAT curve shows its main minimum just before then, centred on 1923. Thus the warming of mean winter NZT of 0·89°C from a minimum in 1901–1902 to a still slowly increasing value in 1993 is somewhat less than the 1·00°C in winter NMAT since 1923, although the NMAT anomaly in 1901–1902 is similar in size to that of the minimum in winter NZT, which also occurred at this time. The SST shows marginally the smallest warming of all seasons at 0·56°C between 1896 and 1993. Mean minimum winter NZT had its lowest values in 1933 whereas mean maximum winter NZT had its lowest values in 1899, similar to mean winter NZT. The warming of these two series is hard to compare because of differences in timing, but has been 1·10°C (maximum) and 0·82°C (minimum) overall. Despite more complex behaviour and problems with NMAT data, there appears to have been a warming of at least 0·8°C in all the winter air temperature series.

Finally Figure 8(f) shows the trends in spring. These show only a small warming in NZT since the late 1950s, though warming still continues, and little trend since that time in the marine values. Total warming is similar for the three data sets (0·66°C for mean NZT, 0·68°C for NMAT, and 0·68°C for SST), although the coolest value of NMAT is centred on 1884–1885 unlike mean NZT and SST whose minima were both in 1902. A secondary minimum centred near 1930, as in winter, is evident in all three series.

Thus the observed warming in mean NZT, and in its marine surroundings, has been close to 0·7°C, has been shared by all seasons with some differences in timing and magnitude, and it has not been linear. We feel that many of the seasonal differences from the annual mean behaviour are likely to be at least qualitatively reliable. It is likely that there was a period of minimum temperature around 1900–1910 in the New Zealand region, as indicated for the global oceans by Bottomley *et al.* (1990) and Folland and Parker (1995). In the New Zealand region, this warming trend has slowed considerably recently, with the exception of winter, and autumn clearly has cooled recently.

NEW ZEALAND TEMPERATURE, ENSO, AND SOUTHERN HEMISPHERE TEMPERATURE

Finally we discuss the likely influences of the El Niño–Southern Oscillation (ENSO) on NZT as measured by an SST index and associations with large-scale temperature changes represented by Southern Hemisphere SST. We also discuss the likelihood that the warm ENSO event of 1991–1993 (in fact this continued into 1995) is related to the two recent very cool years in New Zealand, 1992–1993, which are very evident in the unfiltered temperature data (Figures 3 and 4). Additional discussion to that below appears in Basher and Thompson (1995).

Annual and seasonal variability of NZT has long been linked to the Southern Oscillation (Gordon, 1985). Most recently, Salinger *et al.* (1995) noted that annual temperature anomalies in New Zealand and its outlying islands are positively correlated with the Southern Oscillation Index ($r = 0{\cdot}59$). The area of strongest correlation includes the northern parts of New Zealand and islands to the north and east. These relationships are strongest in spring and weakest in autumn (Salinger *et al.*, 1995), confirming observations by Gordon (1985) and Mullan (1995a). These regional temperature anomalies are a direct consequence of the response of the atmospheric circulation to the Southern Oscillation. On an annual basis, the positive phase of the Southern Oscillation is associated with more frequent east and north-east winds over the region, and the negative phase with more frequent winds from the west and south-west. There is a superimposed seasonal variation in these anomalies between more west/east flow in summer and autumn, and more south-west/north-east flow in winter and spring (Gordon, 1985; Mullan, 1995a, b). Temperature differences between the Southern Oscillation responses are greater between the typical south-west/north-east wind differences seen in winter and spring, than the west/east differences typical of summer and autumn. Thus warm-event ENSO years tend to be cool and cold-event years warm in New Zealand, relative to a contemporary average, with the largest anomalies (on average) in winter and spring.

Salinger *et al.* (1995) further note that 1981–1990 is the warmest decade on record for annual mean NZT (indicated in Figure 7(a)), despite more frequent ENSO episodes and the strong inverse temperature relationship with El Niño. For this region both 1982 and 1983 are cooler than the 30 year running mean but not all ENSO years give a reliable cooling signal (see below). However, the long-lived ENSO event of 1991–1993 (which, as noted above, continued into 1995) did give a major cooling. Hence the shorter term temperature variability is controlled partly by ENSO, consistent with relationships established in other studies (Rasmusson and Carpenter, 1982; van Loon and Shea, 1987; Halpert and Ropelewski, 1992).

Here we use SST anomalies taken from GISST in the tropical east and central Pacific as an ENSO indicator, as foreshadowed near the beginning of this paper. We call this tropical east Pacific SST (TEP SST). The choice of area is justified by, for example, Rasmusson and Carpenter (1982) and the marine temperature eigenvector studies of Hsiung and Newell (1983) and Parker and Folland (1991). We also compare the NZT record with SST anomalies for the whole Southern Hemisphere taken from MOHSST5. Although the present version of GISST can make better use of, and 'fill in', sparse data, if large regions exist with nearly no data for long periods, GISST relaxes SST in these regions towards climatology. So a Southern Hemisphere time series based on GISST probably varies too little. For TEP SST, this problem is judged to be outweighted by the beneficial impact of the data interpolation techniques. We have treated NZT slightly differently from the previous sections. The TEP SST is believed to force New Zealand climate so we have used annual mean values of NZT contemporaneous with TEP SST. Annual NZT is thus based on January to December in this section, despite the result of Gordon (1985) who indicated that annual NZT was best correlated with the Southern Oscillation Index for a year defined to be May to April. Tests show that this does not hold for correlations with TEP SST, so we have used the calendar year. Seasonal values are redefined similarly, so summer is January to March, etc.

The more pronounced warm and cold ENSO events can be defined in various ways. Because of evidence of general warming in the tropical east Pacific (Bottomley *et al.*, 1990), one way to identify the more prominent events is to calculate SST anomalies from a running 30-year average centred on the year in question. The NZT also has been treated this way in order to create Figure 9. For TEP SST we have added 15 years at the beginning and the end of the record, with anomalies equal to the first and last observed 15 years, in order to calculate centred running means starting in 1871 and finishing in 1993. We have treated mean annual NZT similarly except that we have used observed NZT data for 1856–1870. When we do this, 'large' warm-event years (January to December) over 160°W–80°W, 10°N–10°S with an anomaly $\geq 0{\cdot}5$°C higher than the contemporaneous 30 year running mean, were, in 1871–1993: 1877, 1888, 1896, 1902, 1905, 1930, 1941, 1953, 1957, 1958, 1965, 1969, 1972, 1982, 1983, and 1987 (16 years). Large cold-event years, with anomalies of $\leq -0{\cdot}5$°C were 1892, 1893, 1909, 1910, 1950, 1954, 1955, 1956, 1971, 1974, 1975, 1985, and 1989 (13 years).

Figure 9 shows a histogram of the annual mean NZT anomalies divided according to these warm and cold events. These large warm and cold events give a good but not perfect discrimination in annual mean NZT. Cold events tend to be associated with warm NZT and warm events with cold NZT as discussed above, but 1957 and 1987 are 'large' warm event exceptions (NZT anomalies both 0·21°C). 1950 is the only 'large' cold event exception (NZT anomally = $-0{\cdot}04$°C). For the large events the correlation between annual TEP SST and annual

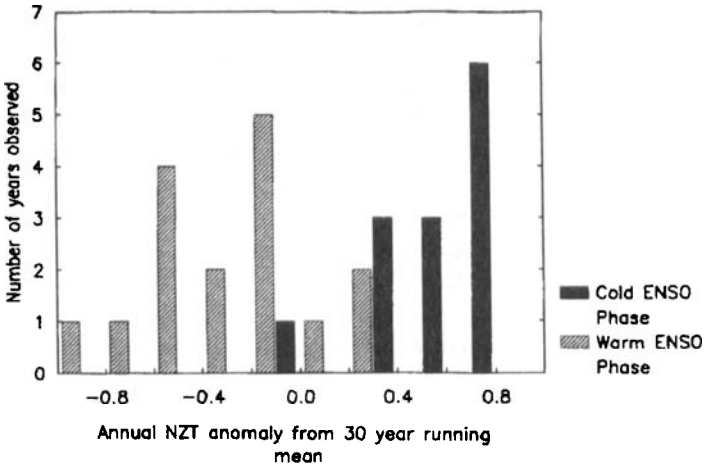


Figure 9. Histogram of annual mean NZT anomalies for years with annual tropical East and central Pacific SST anomalies exceeding 0·5°C in magnitude, 1871–1993. Data are grouped into 0·2°C boxes. Anomalies are deviations from a running centred 30-year average. Solid, cold tropical East Pacific SST; shaded, warm tropical East Pacific SST.

NZT anomalies is −0·79. Thus larger ENSO events are highly correlated with annual NZT but a few exceptions to the expected relationship still exist.

The correlation between annual unfiltered NZT and TEP SST anomalies is only −0·41 for 1871–1993. However, the correlation rises to −0·59 for all data when the anomalies from 30-year centred running means (as above) are used. This indicates that the non-stationarity of the NZT and TEP SST series significantly reduces the 'true' interannual correlation. Table III, for 1901–1993, therefore shows partial correlations between annual mean NZT, TEP SST, and Southern Hemisphere SST anomalies, all from a fixed 1951–1980 average, and the multiple correlation with both. The period 1901–1993 has been chosen because SST data are better, although correlations for 1871–1993 are only slightly lower. The seasonal multiple correlations are less than the annual, as might be expected. Partial correlation with TEP SST is highest in spring at −0·56 followed by winter (−0·48), agreeing with Salinger *et al.* (1995) that the largest effects of ENSO on NZT are in winter and spring.

The partial correlation with Southern Hemisphere SST varies more, being largest in winter (0·56) and smallest in autumn (0·28). Overall the contribution of the two SST variables to the variance of annual NZT is similar. Together they explain about half the annual variance, most seasonal variance in winter and spring (36 per cent and 32 per cent respectively) but only about 20 per cent in summer and autumn.

The time-scales of associations between NZT, Southern Hemisphere SST, and TEP SST are investigated in Figure 10(a–d). Figure 10(a) shows (lightly smoothed) spectra of linearly detrended annual mean NZT and of detrended Southern Hemisphere annual SST for 1871–1993 using the fast Fourier transform method. Figure 10(b) is a similar plot for annual mean NZT and annual TEP SST. All series have been standardized so that the relative variations of variance at different periods are highlighted. The necessary detrending removes the linear component

Table III. Correlations between annual and seasonal New Zealand temperature and tropical East Pacific (TEP) SST and Southern Hemisphere (SH) SST, 1901–1993

Season	Partial Correlations		Multiple correlation
	SH SST	TEP SST	
Summer	0·39	−0·44	0·46
Autumn	0·28	−0·45	0·45
Winter	0·56	−0·48	0·60
Spring	0·42	−0·56	0·57
Annual	0·61	−0·65	0·69

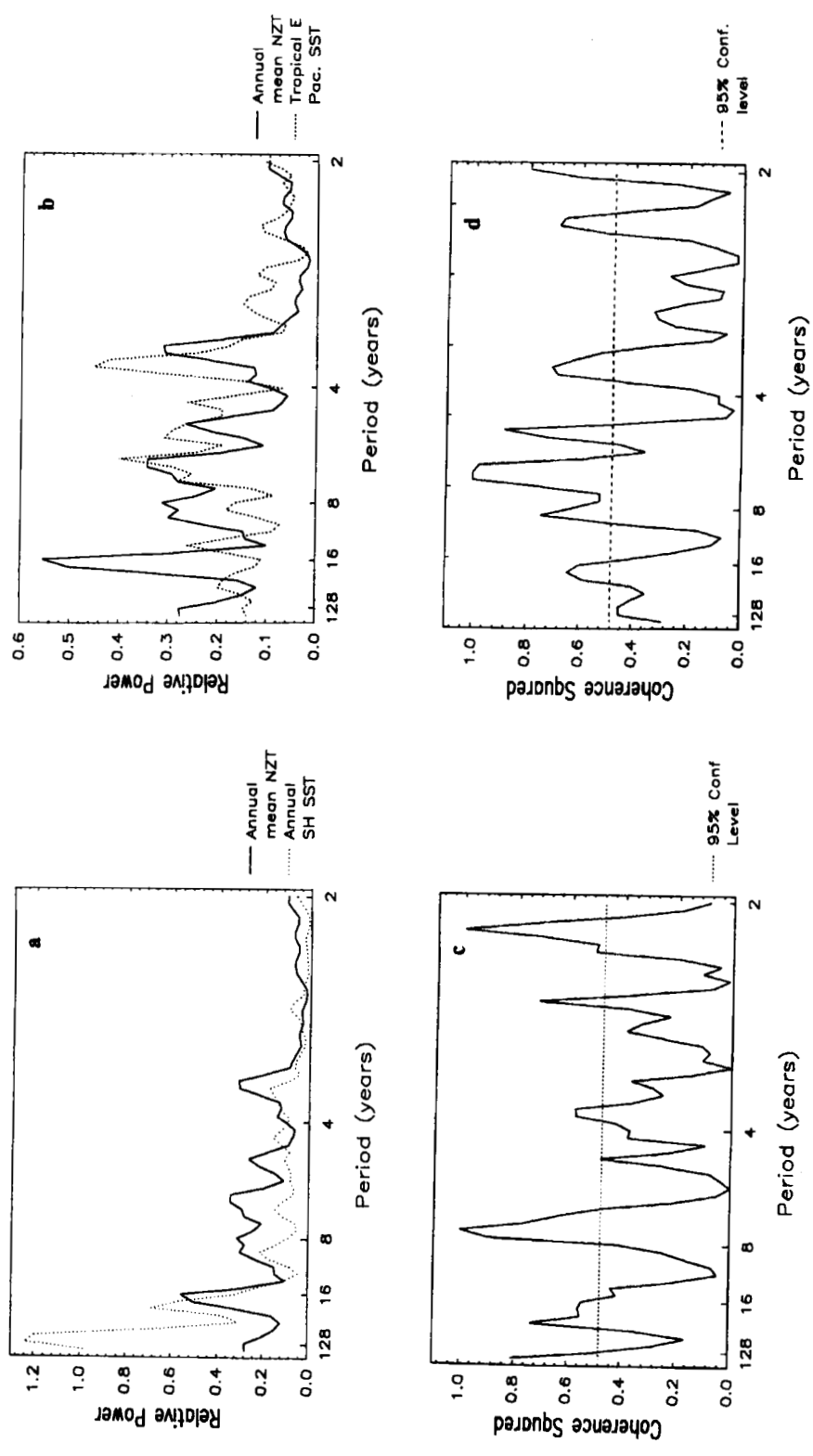


Figure 10. (a) Spectra of annual mean NZT anomalies and annual Southern Hemisphere SST anomalies, 1871–1993. (b) As (a) but tropical East Pacific SST anomalies. (c) Coherence squared between annual mean NZT anomalies and Southern Hemisphere SST, 1871–1993. (d) As (c) but tropical East Pacific SST

of the lowest frequency variance. So the low frequency peak in Southern Hemisphere SST is relatively much greater than that in NZT in Figure 10(a) partly because the former series shows more non-linearity in the low frequency. Interestingly, the pronounced spectral peak in NZT near 16 years is close to but not identical to that in Southern Hemisphere SST. The latter is centred near 21 years, as shown by Folland *et al.* (1984). (The way NZT gives rise to this quasi-16 year peak is evident from Figure 7(a–f)). Southern Hemisphere SST clearly has relatively much less relative variance on time-scales of 3–9 years, although weak peaks exist that are likely to be related to ENSO. Figure 10(b) shows that, as expected, variance in the 3–9 year band is comparable in NZT and TEP SST but is lacking in TEP SST near the prominent quasi-16-year peak in NZT. This quasi-16-year peak (better described as a '1–2 decade' peak) has been little remarked upon in previous studies.

Further information can be gained by studying the coherence between annual mean NZT and the two marine series. Coherence essentially measures the correlation between two series as a function of frequency or period (Bloomfield, 1976). Here we show coherence squared, equivalent to correlation squared, as a function of period (Figure 10(c and d)). High and significant coherence exists between annual mean NZT and annual southern Hemisphere SST at very low frequencies and on time-scales around 6–8 years and on a quasi-biennial time scale (Figure 10(c)). The small variance of NZT at the 21 year time-scale is also coherent with Southern Hemisphere SST but coherence is only marginally significant around 16 years. In Figure 10(d), marginally significant coherence occurs around 16–25 years with the low relative value of annual TEP SST variance on this time-scale. Highest coherence between annual mean NZT and annual TEP SST occurs on ENSO time-scales between 3·5 and about 8 years, and on biennial time-scales, although variance in both NZT and TEP SST is small there.

Thus there is a strong relationship between NZT and TEP SST on ENSO time-scales and with Southern Hemisphere SST on very low frequency and some shorter time-scales that overlap relatively little with those of TEP SST. The cause of the very prominent and persistent one-to-two decades peak in NZT variance remains unclear but Figure 7(a–f) clearly indicates its importance.

THE COOL YEARS 1992–1993

We conclude with a discussion of the recent cold period. The year 1992 (− 0·89°C deviation from the 1951–1980 average) was the coldest since 1930 (− 1·07°C deviation from the 1951–1980 average) according to our definition of NZT. If we use the 30-year running average technique, 1992 was the second coldest calendar year (− 0·97°C) in the whole period 1871–1993 relative to the contemporaneous average, marginally second to 1884 (− 0·98°C). This coolness is believed to be related partly to the persistent warm phase ENSO of 1991–1993. Hay *et al.* (1993) show typical atmospheric circulation anomalies associated with this phase of ENSO. Figure 11(a) shows the anomalies of 850 hPa wind vectors for 1992–1993 relative to a 1984–1990 average taken from the UK Meterological Office operational global analysis; the brief climatological averaging period is due to the fact that operational weather forecasting analyses were first kept in 1984. The anomalous centre of low pressure east of Chatham Island typically associated with ENSO (Hay *et al.*, 1993) is clearly seen, with anomalous south-easterlies in the extreme south of New Zealand. Anomalous southerlies or south-westerlies prevail further north over New Zealand while anomalous westerlies extend far to the east around 30–40°S. Anomalous easterlies (in reality reduced westerlies) can be seen over the South Pacific from South America to near New Zealand between 50°S and 60°S, so the scale of the atmospheric circulation anomalies is that of the South Pacific. The anomalous westerlies over the central and west tropical Pacific typically associated with a warm event also can be seen, with a weak anomalous anticylonic circulation over Australia. Corresponding SST anomalies are shown in Figure 11(b) (anomalies here are from a provisional new GISST climatology for 1961–1990). The SST patterns are very consistent with the wind anomalies in the New Zealand region. The SST anomalies are generally between − 0·25°C and − 0·75°C near New Zealand, with anomalies $< -0{\cdot}5$°C extending far to the east around 30–40°S beneath and to the north of the area of westerly anomalies shown in Figure 12(a). These two diagrams highlight the fact that short term NZT anomalies associated with persistent wind anomalies can be reinforced by a regional SST response.

The years 1992–1993 are coincident with the predicted peak global cooling effects of Mt Pinatubo on global surface temperature (Hansen *et al.*, 1992). It is interesting to note that the coldest year in the NZT record using the 30-year running average technique was 1884, the year after the eruption of Krakatoa in Indonesia. At present there is no reliable method of calculating the general influence of major volcanic eruptions on regional temperature on

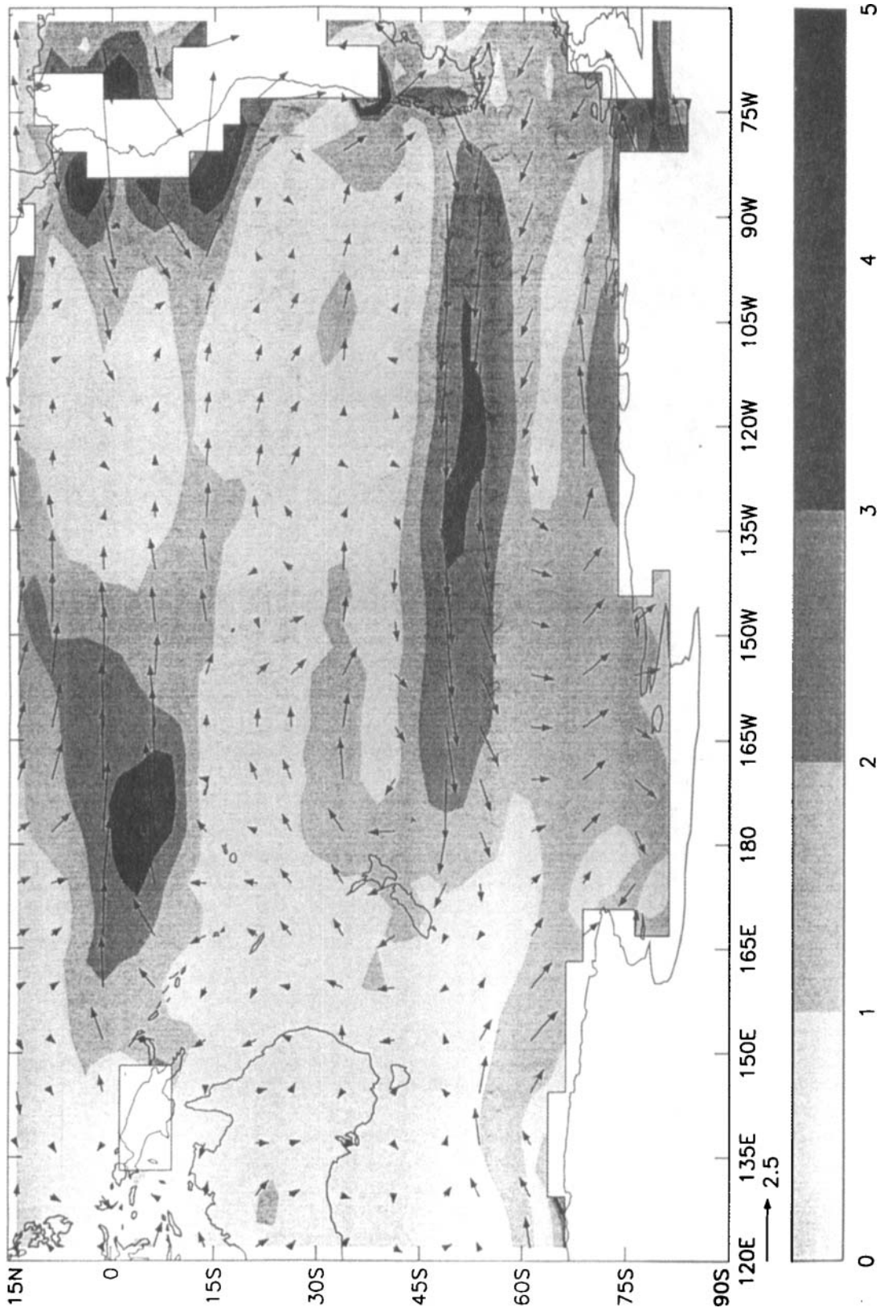


Figure 11. (a) Anomalies of 850 hPa wind in the South Pacific for January 1992 to December 1993 from a 1984–1990 average taken from the UK Meteorological Office operational archive. (b) Anomalies of SST (°C) for January 1992 to December 1993 from a provisional new GISST 1961–1990 average (sea ice not shown)

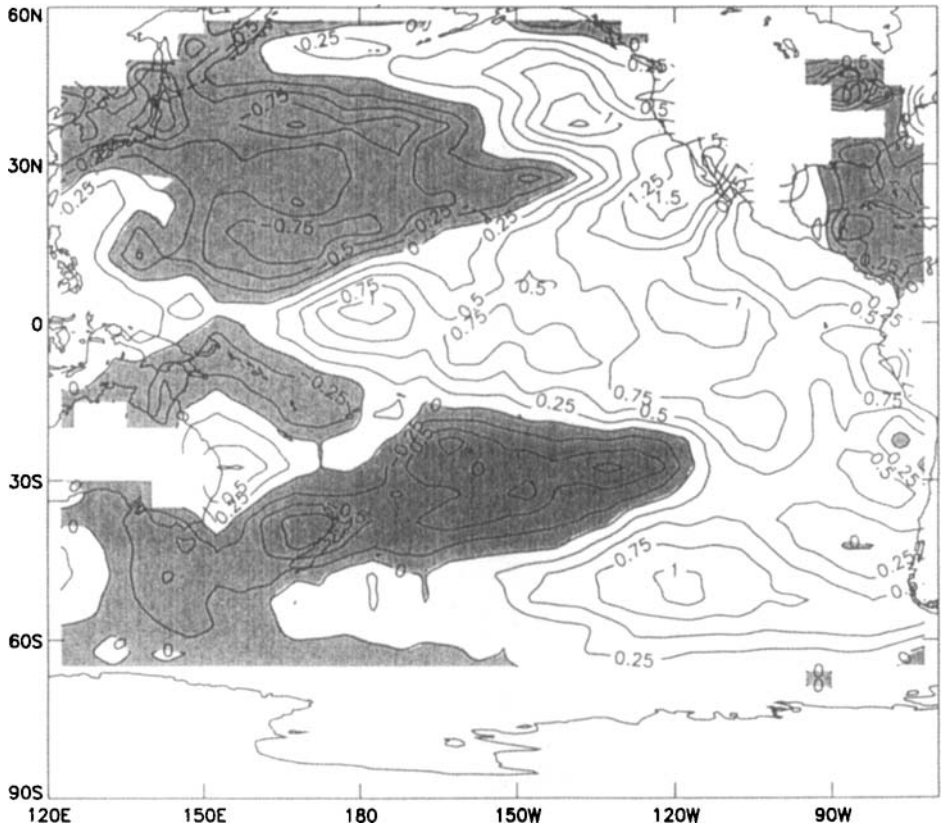


Figure. 11b

the scale of the New Zealand region. This arises not only because of additional regional noise but eruptions can affect the regional atmospheric circulation to give counterintuitive effects on temperature (e.g. Groisman, 1992). However, it now seems likely that Mt Pinatubo briefly cooled marine surface temperatures in the global average by about 0·3°C and continental land temperatures about 0·8°C by the end of 1992 (Houghton *et al.*, 1994; Parker *et al.*, 1996). The only evidence of a direct effect on NZT in 1992–1993 comes from the coupled model predictions of Hansen *et al.* (1992) of the cooling of surface air temperature. Inspection of his diagrams suggests a general cooling of perhaps 0·3°C in the Southern Hemisphere ocean, including the New Zealand region. (ENSO was *not* included in his simulations.) We conclude that there is tenuous evidence for cooling of NZT in 1992–1993 due to Mt Pinatubo of a few tenths of a degree additional to the likely larger effects of ENSO. Further investigation is clearly warranted.

CONCLUSIONS

Our most important result has been to demonstrate that the observed trends and shorter term variations in NZT are in excellent agreement with those of nearby SST and are only in slightly poorer agreement with nearby air temperatures measured by ships at night. We conclude that these three data sets, and especially the first two, have been of high quality in the New Zealand region for most of the last 120 years, apart from a few wartime years for the marine data. An overall warming of annual New Zealand temperature of near 0·7°C this century can be regarded as reasonably well established. The data have been sufficiently consistent to provide plausible verifications of the calculated corrections to SST in the New Zealand region both annually and seasonally. The value of the smaller corrections, of opposite sign, to marine air temperature measured at night is less clear.

There are now very good prospects for further investigating the causes of the observed trends and variations of New Zealand climate using data and climate models. It is very likely that ENSO is an important factor for

influencing atmospheric circulation around New Zealand and for causing temperature fluctuations of opposite phase to those in the tropical East Pacific. However, these effects are sufficiently uncertain that the coincident influence of other factors, such as SST in the remainder of the global oceans, should be investigated. Unpredictable internal atmospheric variability also may be significant. New methods are becoming available to study the SST forcing and internal variability problems (e.g. Rowell *et al.*, 1995). These depend on the use of ensembles of climate model simulations forced with observed SST and sea-ice extent. The long-term warming of New Zealand temperature is clearly related to that of the Southern Hemisphere as a whole during this century, but New Zealand warming has been larger and has evolved somewhat differently. Finally, temperature fluctuations on time-scales around one to two decades which are not obviously strongly associated with ENSO or Southern Hemisphere warming have been shown here to be a prominent part of climate variability over New Zealand. In view of the likely importance of this time-scale to perceptions of climate warming in future years, this phenomenon requires special investigation.

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